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(54) IMPROVEMENTS IN OR RELATING TO THERMALLY-RESPONSIVE ELECTRICAL SWITCHING ARRANGEMENTS

(71) We, OTTER CONTROLS LIMITED, a British Company, of Otters 'Ole, Market Street, Buxton, Derbyshire, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention concerns improvements in or relating to thermally-responsive electrical switching arrangements.

Electrical switching arrangements employing simple thermo-mechanical elements, such as the simple bimetal strip or bourdon tube for example, for opening and closing mechanical switching contacts have been found unsatisfactory for use in control systems where any degree of long-term reliability and stability is required, on account of their inherent disadvantages of contact arcing, which can result in welding of the contacts and causes radio and television interference, and contact wear which leads to long-term drift in the operating characteristics of the arrangement.

To overcome or at least reduce the problems encountered with arrangements employing simple thermo-mechanical elements as discussed above, snap-acting switch actuating elements have been developed, such as the bimetallic switch actuating elements described and claimed in the specifications of British Patents Nos. 600005 and 657434. However, snap-acting switch actuating elements inherently have an operational temperature differential, i.e. their operating temperatures with rising temperature and falling temperature are different. By virtue of this unavoidable temperature differential, the use of snap-acting switches actuating elements involves design difficulties in achieving a finer degree of temperature control than the extent of their temperature differential permits.

In order more readily to achieve better temperature control than can be achieved with switching arrangements employing snap-acting switch-actuating elements, various sophisticated electronic temperature-responsive systems have been developed. These normally employ thermocouples, thermistors or resistance coils to sense the temperature, an amplifier to amplify the small temperature-respresentative signals from the sensor, and a power switching stage, the whole system being powered by a low-voltage power supply unit. Such systems, while capable of giving very precise temperature control, are very expensive, as compared to conventional bimetal switching arrangements for example, and for this reason have not found much application in domestic situations.

This invention aims to obtain the precise temperature control obtained by the electronic systems by taking advantage of the high sensitivity of simple thermo-mechanical elements such as simple bimetal strips, bourdon tubes etc. (as opposed to snap-acting devices) without suffering from the disadvantages inherent in such simple elements and the high cost of sophisticated electronic systems.

Thus the present invention provides a thermally-responsive switching arrangement comprising an electronic switch for switching the current through a load, a triggering circuit for effecting the switching of the electronic switch, the triggering circuit including a variable inductance connected in the circuit in such a manner that the triggering of the electronic switch depends upon the value of the variable inductance, and a thermo-mechanical transducer associated with said inductance to vary the value thereof in dependence upon the temperature.

As employed herein the term thermo-mechanical transducer is to be construed as denoting a transducer device which produces sensible mechanical movement as the result of changes in temperature. Examples of such devices are bimetal strips, bourdon tubes, pneumatic phials etc.

Also as employed herein the term "electronic switch" is intended to distinguish from mechanical switches employing make and break contacts and to include all non mechanical controllable switches. Thus, for example, the

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electronic switch may be any of the well known solid state thyristor devices, such as a silicon controlled rectifier (S.C.R.), or a triac or may even be a thyratron valve. The electronic switch may also comprise a suitably rated power transistor, in which case the arrangement according to the invention could be adapted to effect proportional control of the supply of power to effect proportional control of the supply of power to a load in response to temperature changes. However for domestic applications, where current flowing through a load (e.g. a heater) powered from the alternating current mains supply is to be controlled, it is preferred to employ a triac since this type of electronic switch is capable of passing current in both directions, i.e. in both half-cycles of the a.c. supply waveform.

The variable inductance may, for example, comprise a single coil and core whose inductance—and hence impedance—is variable by virtue of the core being movable relative to the coil, or vice-versa, by means of the thermo-mechanical transducer, the transducer being mechanically connected to both the coil and the core to effect relative movement therebetween as the temperature changes. In another form, the core may be in two parts which are movable relative to one another by means of the thermo-mechanical transducer as the temperature changes so as to alter the reluctance of the magnetic flux path linking the coil and hence alter the inductance of the coil.

Alternatively the variable inductance may be a transformer in which the mutual inductance between the primary and secondary windings is variable by means of a suitable thermo-mechanical transducer as the temperature changes. One form of such a variable transformer has a pair of coils positioned adjacent one another and a common core which is movable relative to the coils in a manner similar to that described above for the single coil. Another form of variable inductance transformer is one in which the transformer core itself is formed in two parts, the primary and secondary windings of the transformer being wound either both on one core part or one on each core part, and the two parts are movable relative to one another by means of the thermo-mechanical transducer as the temperature changes so as to alter the reluctance of the magnetic flux path between the primary and secondary windings of the transformer and hence alter the mutual inductance between the windings. Thus, for example, the thermo-mechanical transducer may be a cantilevered bimetallic strip carrying at its free end one part of the transformer core, the other part of said core being fixed and the two parts of the core being positioned close to one another such that movement of the bimetallic strip due to change of temperature alters the reluctance of the magnetic flux path between the coils.

In yet another form the variable inductance may comprise a coil (or, in the case of a variable transformer, two or more coils) with a core together with a short-circuit turn arranged in such a manner that relative movement of the coil assembly and the short-circuit turn causes the inductance to vary as the temperature changes. The short-circuit turn may be made of any suitable material, and may, for example, be attached to the thermo-mechanical transducer to be moved thereby. Alternatively, the thermo-mechanical transducer itself may be arranged to form the short-circuit turn; thus, in the case of a bimetallic strip for example, a hole may be arranged in the strip and the strip positoned relative to the coil assembly such that the magnetic flux links the short-circuit turn formed by the material of the strip surrounding the hole. Where the bimetal does not in itself provide a suitable conducting path it may be re-inforced by a short-circuit turn of suitable material arranged or attached concentric with the hole.

For controlling the power supplied to a load from an a.c. supply, the trigger circuit in the switching arrangement according to the invention is designed to supply a trigger pulse or a number of trigger pulses to the variable inductance during each operative half-cycle of the supply and the current passed through the variable inductance is used to trigger the electronic switch, the amplitude of the current being dependent upon the setting of the variable inductance as determined by the thermo-mechanical transducer.

Thus in one basic embodiment of the invention, triggering signals are derived by using the waveform of the a.c. supply being switched as a suitable triggering source. In this embodiment, the primary of a variable inductance transformer is supplied by the supply voltage, suitably dropped via resistors. The a.c. signal appearing at the secondary is then applied to the gate electrode of a controlled rectifier constituting the electronic switch to control the switching thereof: in operation of this embodiment, the supply of current to a load will either be established substantially fully or will not be established at all during each half cycle of the supply depending on the state of the transformer at the start of the half cycle.

The switching on of the load current may advantageously be arranged to occur at a predetermined point in each half cycle irrespective of when the thermo-mechanical transducer moves to the switch-on position, i.e. if the transducer moves to the switch-on position at a time in a half-cycle later than the predetermined point, the switch-on will not occur until the predetermined point in the next following half-cycle. By choosing the pre-determined point early in the half-cycle, ideally at zero cross-over voltage, large switching surges can be avoided. Also, irrespective of when the transducer moves to the switch-off position, the switch-off can be arranged to occur

naturally at or near the next following zero cross-over by normal electronic switching action again avoiding large switching surges. Thus, in an embodiment of the general type in which the load is either fully powered or not powered at all during each half cycle, a capacitor may be connected to be rapidly charged from the supply to the breakdown voltage of a trigger diode for supplying triggering pulses to the primary of the transformer, and, once the trigger diode has broken down, it may be arranged to remain in the holding state for the rest of the half-cycle such that only one trigger pulse per half-cycle is produced. This allows the switch-on of the load only at the pre-determined point in the half-cycle (normally arranged at or near the start of the half-cycle by judicious choice of trigger diode and phase shift components) irrespective of when the transducer reaches its switch-on position.

In other embodiments of the invention means are provided whereby the power delivered to a load from an a.c. supply is continuously varied with change of temperature by phase control of the electronic switch, i.e. by varying the time in each operative half-cycle of the a.c. supply during which the electronic switch is switched on. In these embodiments a trigger signal consisting of a series of pulses of variable amplitude superimposed on a ramp having a predetermined fixed gradient is derived. The amplitude of the pulses is varied with change of temperature in a manner similar to that described above, so that the time at which the electronic switch switches on in each operative half-cycle is continuously variable as a function of the temperature. Where both positive and negative half-cycles of the supply are utilized to power the load and trigger pulses are arranged to be positive and negative in positive and negative half-cycles of the supply respectively, and similarly the gradient of the ramp is alternately positive and negative in alternate half-cycles.

In order that the invention might be better understood five embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:—

Figure 1. shows one embodiment of a thermally responsive switching arrangement according to the invention which employs the a.c. current supplied to the load to trigger the electronic switch.

Figure 2. shows a second embodiment similar in function to that of Figure 1 and incorporating synchronous switching at a predetermined point in the half-cycle irrespective of when the thermo-mechanical transducer moves to the switch-on position;

Figure 3 shows a modified form of the embodiment of Figure 2;

Figure 4 shows a thermally responsive switching arrangement according to the invention which incorporates phase control; and

Figure 5. shows a modified form of the thermally responsive switching arrangement of Figure 4.

Figure 1 illustrates one embodiment of a switching arrangement according to the invention in which an electronic switch in the form of a triac 1 is caused to switch a current to a load 2.

A variable inductance transformer 3 is provided in the trigger circuit of triac 1. The primary of the transformer is arranged, with resistor 4, to provide a potential divider across the a.c. supply in such a manner that an a.c. voltage of suitable peak amplitude appears across the primary. This voltage is coupled to the secondary and passes to the gate of the triac via a resistor 5, which is included for current limiting purposes.

Transformer 3 is so constructed that the mutual inductance between the primary and secondary windings thereof is variable by means of a thermo-mechanical transducer, i.e. a device which converts changes of temperature into mechanical movement. Such devices are well known in the art and include the bimetallic strip and the Bourdon tube. Change of mutual inductance with temperature may be achieved, for example, by forming the transformer core in two parts and arranging the two core parts to be moveable relative to one another by the transducer to alter the reluctance of the magnetic flux path between primary and secondary of the transformer, and thus change the coupling between the coils as the temperature changes. By careful choice of the turns ratio of variable transformer 3 and the value of resistor 4, the circuit of Figure 1 can be arranged so that, at a predetermined temperature, the coupling between the primary and secondary of transformer 3 is such that a signal is provided on the gate electrode of triac 1 which is just sufficient to switch triac 1 on and so pass current to the load. Depending on the application, the coupling may be arranged to be increased at lower temperatures and reduced at higher temperatures or vice versa so as to increase or reduce respectively the amplitude of the triggering signal applied to the gate of the triac. By virtue of its inherent bidirectional assymmetry, the triac can take up any of three switching states depending upon the amplitude of the triggering signal, viz

(i) OFF, where the coupling is insufficient to trigger the triac in either positive or negative half-cycles of the a.c. supply.

(ii) HALF ON, where the coupling is sufficient to trigger only on that half-cycle of the a.c. supply to which the triac is more sensitive; and

(iii) ON, where the coupling is sufficient to trigger the triac on both half-cycles of the a.c. supply.

In dependence upon the phase relationship between the primary and secondary of the

variable transformer, the triac can have two alternative triggering modes in which the triac gate voltage is either in phase or out of phase with the AC supply and the triac's sensitivity is different for the two modes. Thus by reversal of the phase between the primary and the secondary of the transformer, two different ranges of switching states may be achieved.

A capacitor 6 may be connected in parallel with resistor 4 to advance the phase of the gate current to ensure switching of the triac early in each half-cycle in which the gate current is sufficient to trigger the triac.

Figure 2 illustrates an alternative embodiment to that of Figure 1 in which a resistance 9, a capacitor 8 and a silicon bilateral switch 7 are used to produce alternate positive and negative pulses for triggering the triac 1 in respective positive and negative half-cycles of the a.c. supply through a variable transformer 3.

The operation of the arrangement of Figure 2 is as follows: as the voltage rises at the beginning of each half-cycle of the a.c. supply, capacitor 8 charges through resistor 9 with a time constant much smaller than the duration of a half-cycle. When the breakover voltage of the silicon bilateral switch 7 is reached, capacitor 8 discharges via switch 7, resistor 10 and the primary of the variable inductance transformer 3. Thus, during discharge of capacitor 8 a pulse of current whose amplitude is dependent upon the state of the transformer is applied via the variable coupling of the transformer to the gate electrode of the triac to trigger the triac. Resistors 5 and 10 are provided for current limiting. After capacitor 8 has discharged the silicon bilateral switch 7 holds in its low resistance state thus clamping the voltage at the junction of capacitor 8 and resistor 9 until the current supplied by the a.c. supply to the switch 7 drops to below the holding current of the silicon bilateral switch whereupon the switch 7 reverts to its high resistance state in preparation for the next half-cycle sequence.

A capacitor 4 may be connected in parallel with resistor 9 to advance the phase of the voltage applied to the silicon bilateral switch 7 to ensure switching of the triac 1 at a point early in each half-cycle in which gate current is sufficient to trigger the triac. Moreover, since only one pulse per half-cycle is produced by the triggering circuit, the load 2 is switched on only at this predetermined point irrespective of when the variable inductance transformer 3 reaches its switch-on state.

As before, reversal of the phase of the windings of transformer 3 gives rise to two alternative triggering modes.

Figure 3 illustrates another embodiment whose operation is similar to that of Figure 2. In this case, the trigger circuit is powered direct from the mains supply, and capacitor 17, resistor 9 and resistor 18 in conjunction with capacitor 8 determine the point in the half-cycle at which the silicon bilateral switch 7 reaches its breakdown voltage. As for Figure 2, the variable inductance transformer 3 determines whether the triac 1 is switched on or not when the trigger pulse is generated. Also, phase reversal of the windings of transformer 3 gives rise to two alternative triggering modes.

Figures 4 and 5 illustrate two forms of switching arrangement according to the invention in which a.c. phase control is employed, i.e. the instant in each half-cycle of the a.c. supply at which the triac 1 turns on is controlled, as opposed merely to controlling whether the triac is switched on or off in each half-cycle as with the previous two embodiments. In this way, the power supplied to a load 2—for example a fan—may be continuously controlled in accordance with the temperature of the surroundings.

The operation of the circuit of Figure 4 is similar to that of Figure 2 in so far as capacitor 8 is caused to charge up from the supply through resistor 9 with a time constant much shorter than that of a half-cycle of the a.c. supply. However, a bilateral trigger diode (diac) 11 is used in place of the silicon bilateral switch of Figure 2. When the breakover voltage of the diac 11 is reached the diac allows capacitor 8 to discharge a pulse of current through to the primary of transformer 3. The diac current is not high enough to reach a holding value, so the diac reverts to its high resistance or OFF state and allows capacitor 8 to charge up again via resistor 8 until the breakover voltage of the diac is reached once more. Thus, for each half-cycle of supply waveform a number of pulses of current will occur at the primary of transformer 3. The exact number of pulses in each half-cycle is dependent on the time constant of capacitor 8 and resistor 9.

At the secondary of the transformer 3, the capacitor 12 is caused to charge up from the supply voltage through resistor 13 with a relatively slow time constant to form a voltage ramp at the junction of capacitor 12 and resistor 13. The aiming voltage of the ramp is set by resistors 13 and 14 which form a potential divider across the supply.

Thus the resultant voltage waveform at the secondary of transformer 3 is a series of pulses superimposed on a ramp, the gradient of the ramp and the polarity of the pulses being alternately positive and negative for respectively positive and negative half-cycles of the supply waveform. The amplitude of the pulses is, as before, dependent on the coupling between the primary and secondary of transformer 3 and hence the temperature of the surroundings. Hence as the amplitude of the pulses at the secondary of transformer 3 is varied with temperature variations, the time in the cycle at which the triac is switched on will be varied

likewise, so that the triac is phase controlled.

For some applications the ramp gradient and/or aiming voltage may also be controlled in response to manual adjustment or to change in some external condition (e.g. temperature) in which case the value of resistors 13 and 14 or of capacitor 12 may be arranged to change in accordance with the change of requirement or of external condition. In the case of the change of ramp being required for change in temperature resistor 13 may, for example, be replaced by a thermistor.

Figure 5 shows an alternative means of achieving phase control. In this case the time constant of resistor 9 and capacitor 16 is made large compared with that of resistor 9 and capcitor 15. Capacitor 15 thus charges up quickly via the resistor 9 until the diac 11 switches on momentarily to pass a pulse of current to the primary of transformer 3. As before, a number of pulses of current are arranged to pass in each half-cycle of the supply waveform. Meanwhile, the capacitor 16 is charging up slowly via resistor 9 to give a ramp voltage at the junction of capacitors 15 and 16. Hence the voltage at the secondary of transformer 3, and hence at the gate of triac 1 is the same as that specified above with reference to Figure 4. In this case the time constant of capcitor 15 and resistor 9 determines the number of pulses per half-cycle. The resistor 10 may vary the sensitivity or limit the current.

Triacs suffer from the disadvantage that they are themselves temperature sensitive to gate voltage and current. In particular a triac requires less gate current to cause it to switch the higher the temperature. Thus when a triac is carrying a power load, it heats slightly due to resistance losses and consequently reduces the gate current required to maintain switching.

In order to reduce the effect of this phenomenon on the arrangement described above a silicon bilateral switch may be interposed in the gate lead to the triac between the variable transformer 3 and triac 1. This modification may, of course, be carried out for any of the above described embodiments. Insertion of the silicon bilateral switch has the effect of limiting the sensitivity of the arrangement to load current since the circuit now switches only on the trigger voltage of a non-power device. A further improvement is achieved by this means since the silicon bilateral switch is inherently much less affected by ambient temperature changes than the triac.

The provision of this extra device would only be necessary in cases where extremely accurate temperature control is required, since, using a sensitive thermo-mechanical transducer of the type herein described, it is unlikely that the temperature sensitivity of the triac would be a problem for most applications.

WHAT WE CLAIM IS:—

1. A thermally responsive switching arrangement comprising an electronic switch for switching the current through a load, a triggering circuit for effecting the switching of the electronic switch, the triggering circuit including a variable inductance connected in the circuit in such a manner that the triggering of the electronic switch depends upon the value of the variable inductance, and a thermo-mechanical transducer associated with said inductance to vary the value thereof in dependence upon the temperature.

2. An arrangement as claimed in claim 1 wherein the variable inductance comprises a coil and a core arranged for relative movement therebetween by the thermo-mechanical transducer.

3. An arrangement as claimed in claim 2 wherein the core is arranged in two parts which are movable relative to one another by means of the thermo-mechanical transducer.

4. An arrangement as claimed in claim 1 wherein the variable inductance comprises a transformer in which the mutual inductance between the primary and secondary windings is variable by the thermo-mechanical transducer.

5. An arrangement as claimed in claim 4 wherein the transformer has two coils positioned adjacent one another and has a common core which is movable relative to the coils.

6. An arrangement as claimed in claim 4, wherein the transformer has a core formed in two parts, the primary and secondary windings of the transformer being wound either both on one core part or one on each core part, and the two core parts are movable relative to one another by means of the thermo-mechanical transducer.

7. An arrangement as claimed in any of the preceding claims adapted for controlling the supply of power to a load from an alternating current (a.c.) supply, and wherein the trigger circuit is adapted to supply a triggering signal to the variable inductance during each operative half-cycle of the a.c. supply and the current passed through the variable inductance is used to trigger the electronic switch, the amplitude of said current being dependent upon the setting of the variable inductance as determined by the thermo-mechanical transducer.

8. An arrangement as claimed in claim 7 wherein triggering signals are derived from the a.c. supply waveform, the primary winding of a variable inductance transformer constituting said varable inductance being supplied by the a.c. supply voltage and the a.c. signal appearing at the secondary winding of the variable inductance transformer being applied to the gate electrode of a controlled rectifier constituting said electronic switch to control the operation thereof.

9. An arrangement as claimed in claim 7

or 8 wherein the switching on of the load current is arranged to occur at a predetermined instant in each operative half-cycle of the a.c. supply such as to avoid large switching surges being produced.

10. An arrangement as claimed in claim 9 wherein the trigger circuit includes a capcitor connected to be rapidly charged from the a.c. supply to the breakdown voltage of a trigger diode for supplying triggering signals to the variable inductance, and the trigger circuit is so arranged that, once the trigger diode has broken down at said predetermined instant, it remains in its conductive state for the remainder of the half-cycle so that only one trigger pulse is produced in each operative half-cycle.

11. An arrangement as claimed in claim 7 wherein means are provided whereby the power delivered to the load is continuously variable with change in temperature by phase control of the electronic switch (i.e. by varying the time in each operative half-cycle of the a.c. supply during which the electronic switch is switched on).

12. An arrangement as claimed in claim 11 wherein said triggering circuit is adapted to derive a triggering signal consisting of a series of pulses of variable amplitude superimposed on a ramp waveform, and the amplitude of said pulses is arranged to be variable with temperature change by virtue of the pulses being passed to said variable inductance, whereby the time at which the electronic switch switches on in each operative half-cycle of the a.c. supply is dependent upon the temperature.

13. An arrangement as claimed in any of the preceding claims wherein the electronic switch is a triac.

14. An arrangement as claimed in claim 13 including a silicon bilateral switch connected in the gate lead of the triac for compensating for the temperature-sensitivity of the triac in regard to gate voltage and current.

15. A thermally responsive switching arrangement substantially as herein described with reference to Figure 1 or 2 or 3 of the accompanying drawings.

16. A thermally responsive switching arrangement substantially as herein described with reference to Figure 4 or 5 of the accompanying drawings.

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FIG.1.

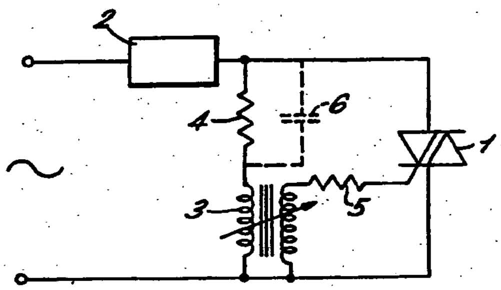

FIG.2.

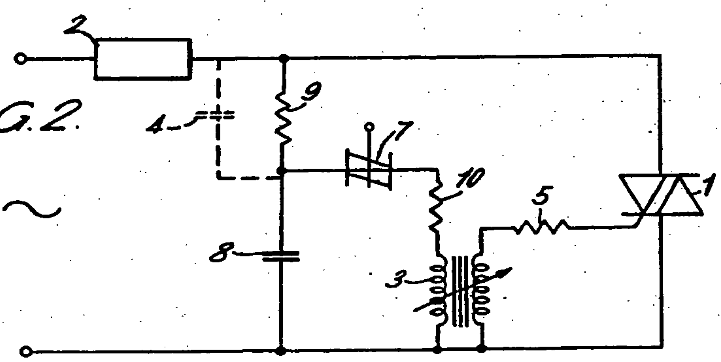

FIG.3.

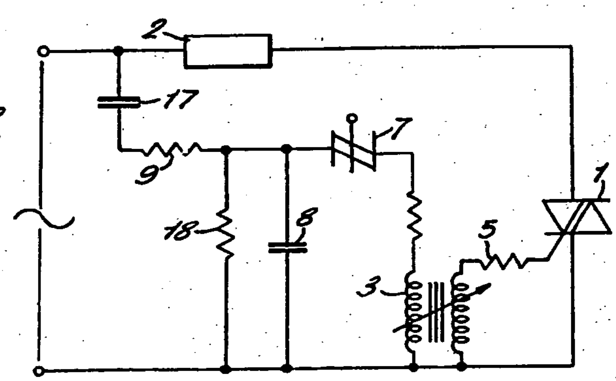

FIG. 4.

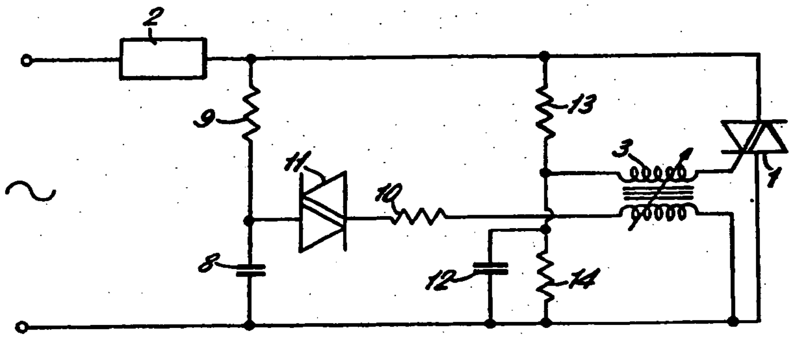

FIG. 5